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Highly efficient parametric amplification and wavelength conversion have been demonstrated in the 1040–1090 nm band. A nonlinear photonic crystal fiber was used to provide the anomalous dispersion required for phase matching at 1 μm. A 40 dB maximum gain and +35 dB idler conversion efficiency have been achieved in the subnanosecond pulsed regime and by using a spectrally filtered supercontinuum source as a small signal. © *2009 American Institute of Physics.*
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Fiber optical parametric amplifiers (FOPAs) and wavelength converters have a number of qualities that make them attractive for all-optical signal processing and ultrafast optics.[1,2] Their advantages over other rare-earth-doped fiber amplifiers include a broad gain bandwidth and access to arbitrary wavelength ranges. First attempts have been made in the 1970s in the visible domain by use of birefringent or multimode fibers[3] and later in the 1.3 μm window with single-mode fibers (SMFs).[4] But now, most of FOPAs are being developed in the 1.55 μm band to meet the requirements of the telecommunication industry. Despite the number of potential applications in the 1 μm band (ytterbium and YAG wavelengths),[5] however, it is remarkable that no experimental demonstration of fiber-based parametric amplifier operating at 1 μm has been done yet. Supercontinuum (SC) generation and four-wave mixing with subsequently parametric gain at 1315 nm have been reported so far.[6] Here, we experimentally demonstrate highly efficient optical parametric amplification and wavelength conversion in the 1040–1090 nm range. This is achieved by pumping at 1064 nm near the zero-dispersion wavelength (ZDW) of a photonic crystal fiber (PCF). Our experimental results show a 40 dB maximum parametric gain and a 35 dB idler conversion efficiency with a high signal-to-background ratio. This fiber-optic pulsed-pump parametric device provides efficient amplification and conversion at 1 μm for potential applications such as optical parametric chirped-pulse amplification,[7] pulse optical replication or regeneration, and ultrafast optical gating or sampling.[8]

To demonstrate the scalar OPA in fiber in the 1 μm region, we have to satisfy several criteria, namely, the phase-matching condition in the anomalous group-velocity dispersion regime and a high nonlinear coefficient to provide efficient parametric gain. At such a wavelength, anomalous dispersion can be provided only by the use of a PCF whose photonic crystal cladding ensures a high field confinement together with the required dispersion characteristics. Microstructured fibers allow such a control of the dispersion characteristics, opening up a wide field of possibilities for fiber-based parametric interactions.[9] Our PCF was manufactured to provide both very small anomalous dispersion and dispersion slope (β_3) at pump wavelength. Its cross-section image is depicted in Fig. 1 together with its dispersion curve. The pitch and holes diameters are 4.13 and 2.61 μm, respectively. Its nonlinearity coefficient γ was evaluated at $\gamma = 12\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$. The fiber loss was evaluated at 15 dB/km at the pump wavelength. Because of its small core diameter and large air-fill fraction, the ZDW is centered at 1063 nm ($\beta_3 = 0.56\ \mathrm{ps}^3\ \mathrm{km}^{-1}$), as shown by the solid line in Fig. 1. To pump our PCF in the vicinity of the ZDW, we used a Q-switched powerchip laser emitting 450 ps pulses (full width at half maximum) at a central wavelength of 1064 nm. The average power of the 1 kHz pulse train exceeds 60 mW. The complete gain measurement setup is depicted in Fig. 2. The signal to be amplified is obtained by propagation of half of the laser power into another 3-m-long PCF such as to generate a SC pulse with nearly the same temporal duration.[6,10] Because the PCF used to generate that SC exhibits a ZDW near 1064 nm as the one used for OPA, the SC

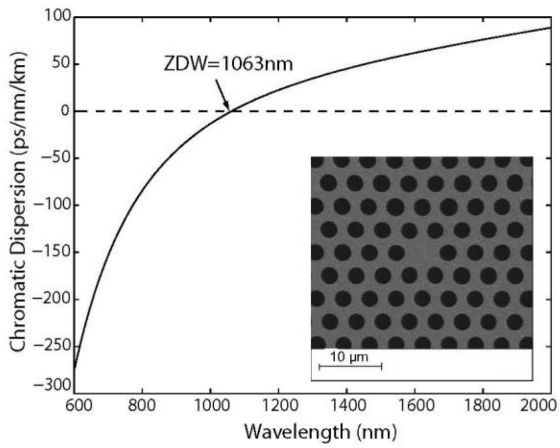

FIG. 1. Chromatic dispersion vs wavelength. Inset: SEM image of the solid-core PCF.

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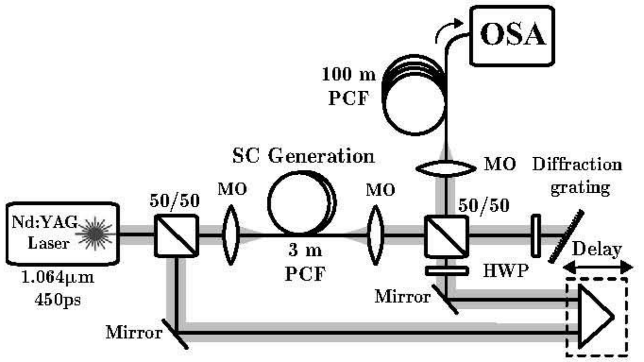

FIG. 2. Experimental setup. MO denotes microscope objective (×20), OSA denotes optical spectrum analyzer (0.1 nm resolution), and HWP denotes half-wave plate.

spans from the visible to the infrared region and is quite flat around the pump wavelength. The SC pulse is spectrally dispersed by a diffraction grating before being launched into the PCF parametric amplifier. The diffraction grating (1500 lines/mm) is adjustable such that only a small tunable fraction of the SC is coupled into the amplifier and that the residual pump that is present in the SC is eliminated. Note that the PCF's core directly acts as a narrow-band spectral filter such as the small signal launched into the PCF has a 0.5 nm 3 dB spectral width. Maximum throughput is ensured by control of the incident polarization with a half-wave plate at the input of the diffraction grating. Because the parametric gain is polarization dependent, a second half-wave plate is also used to align the signal polarization with that of the linearly polarized pump wave. The PCF parametric amplifier is pumped by the remaining half-power of the Q-switched laser, which is combined with the signal through a 50/50 beam splitter. We superimpose the pump and the signal pulses temporally at the entrance of the amplifier by adjusting the air delay line that has been incorporated into the pump path. A peak pump power of as much as $P=10$ W is coupled into the 100-m-long amplifier, while the power density of the input signal is typically kept 40 dB below that of the pump beam. This low signal power together with the short amplifier length guarantees that our measurements are performed in the small-signal gain limit. We obtained the amplifier gain simply by monitoring the signal's output power on a spectrum analyzer, while tuning the pump on and off. The peak pump power was assessed from the measurement of the average output pump power and also by considering both the fiber and splice losses.

We first performed a measurement of the parametric gain bandwidth by tuning the signal wavelength and by keeping the peak pump power constant to about 6 W. All our results are presented as filled circles in Fig. 3(a) as a function of wavelength and are superimposed on the standard theoretical gain curve given by[2]

$$G = 1 + \left(\frac{\gamma P}{g}\sinh(gL_{\mathrm{eff}})\right)^2, \tag{1}$$

where $g^2=(\gamma P)^2-(\kappa/2)^2$ is the parametric gain factor and $\kappa=\beta_2\Omega^2+2\gamma P$ is the phase mismatch. $\beta_2=-2.1\times10^{-28}$ s^2 m^{-1} is the group-velocity dispersion coefficient at the pump wavelength. $L_{\mathrm{eff}}\simeq 85$ m is the effective length that accounts for fiber loss.[11] As can be seen, the agreement between experimental data and theoretical prediction is very good. In particular, a maximum 35 dB gain and a full gain bandwidth over the range of 1040–1090 nm are obtained for that pump power. The gain band is perfectly symmetric because the pump power used in our experiment is well below the Raman threshold power ($P_{\mathrm{Th}}=28$ W). As an example, Fig. 3(b) shows typical amplifier's input and output spectra for a signal wavelength at 1078 nm that corresponds to the point indicated by an arrow in Fig. 3(a). Note in particular that the signal spectrum exhibits a high signal-to-background ratio (55 dB) because the pump power is kept just below the modulation instability threshold, or equivalently parametric amplified spontaneous emission (ASE). By looking carefully at the pedestal signal spectrum however, we can see residual parametric ASE noise. We can also see on Fig. 3(b) two additional symmetric sidebands at 1092 nm and 1039 nm, respectively. These sidebands are generated by cascaded four-wave mixing involving the signal, idler, and pump waves.[12] This means that the parametric amplifier operates in the high conversion regime.

To complete these preliminary results, we additionally measured the pump power dependence of the parametric gain and idler conversion efficiency, respectively. To this end, we choose a signal wavelength at 1081 nm which corresponds to the maximum of the gain curve shown in Fig. 3. Figure 4 shows the results in function of the peak input pump power. As expected from theory, the parametric gain exponentially grows with the pump power, until about 40 dB. At higher pump power, it saturates because of both pump deple-

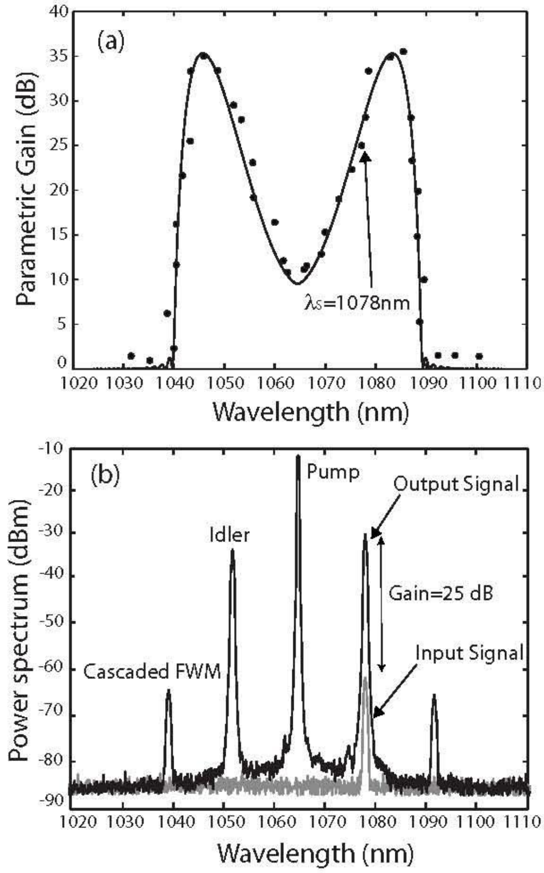

FIG. 3. (a) Gain spectrum of the PCF-based parametric amplifier at $P=6$ W. Circles denote experimental results. Solid curve denote standard analytical gain theory. (b) Input and output spectra for a signal wavelength located at 1078 nm.

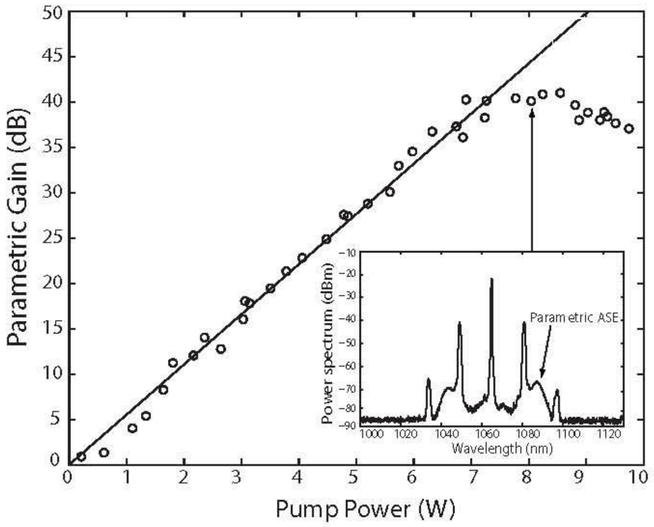

FIG. 4. Experimentally measured parametric gain vs the peak pump power for a signal wavelength at 1081 nm. Signal input power=−78 dBm. The solid line is a linear theoretical fit. Inset: saturated FOPA spectrum indicated by the arrow.

tion and parametric ASE noise, as shown in the spectrum illustrated in the inset of Fig. 4. A maximum 35 dB wavelength conversion efficiency was also evaluated through measurement of the idler spectral power.

To conclude, we have demonstrated a highly efficient PCF-based OPA and wavelength converter operating in the 1040–1090 nm range. 40 dB maximum parametric gain and 35 dB conversion efficiency have been demonstrated using a low-power Q-switched subnanosecond microchip laser. Although this preliminary experiment used subnanosecond pulses, we are confident that it can still operate in the femtosecond regime or even in the continuous-wave regime. This will require the use of $LiNbO_3$ phase modulator in the near infrared for suppressing Brillouin backscattering and high-power ytterbium fiber amplifier in combination with longer microstructured fibers. We hope in this way to move toward an all-fiber parametric device for practical usefulness at 1 μm. Finally, broader bandwidth could in principle be obtained by managing the third and fourth-order dispersion coefficient of the fiber.

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